

## **Chapter 4**

### **EPA Pilot-Scale Experimental Approach and Equipment**

A series of combustion tests were conducted at the NRMRL combustion research facilities in Research Triangle Park, NC to provide data on emissions from Orimulsion and heavy fuel oil generated in a single combustion system under controlled conditions.

#### **Approach**

The approach chosen for the test program was to measure emissions from the two formulations of Orimulsion and a commercially available heavy fuel oil in a single test combustor. This approach was believed to result in data that would allow direct comparison of the impact of the different fuels on air pollutant formation and emissions. By using this approach, changes in emissions due to different burner or combustor design parameters would be eliminated, and the only significant factors remaining would be the combustion conditions and the fuels.

Each test condition was run four times to allow the repeatability of the test condition and results to be quantified. Flue gas constituents and properties to be measured were CO, CO<sub>2</sub>, NO<sub>x</sub>, O<sub>2</sub>, PM, SO<sub>2</sub>, SO<sub>3</sub>, and THC concentrations; particle size distributions; concentrations of As, Be, Cd, Cr, Cu, Fe, Mn, Mg, Ni, Sb, V, and Zn; and concentrations of volatile and semivolatile organic compounds. Table 4-1 shows the test matrix developed for the test program, with the number of measurements of each of the above constituents or parameters and the methods used in quantifying each constituent or parameter.

#### **Test Equipment**

All tests were conducted on a single research combustor under test conditions that were held as constant as possible. Some differences were anticipated due to differences in combustion characteristics between Orimulsion and heavy fuel oils. Operating at conditions appropriate to each fuel was viewed as more desirable than maintaining a single condition, since real world operation would adjust combustion conditions to achieve optimum performance based on the particular fuel. In particular, O<sub>2</sub> level was intended to be set based on the minimum O<sub>2</sub> that could be achieved without generating excessive CO. "Excessive" CO was defined to be approximately 50-100 ppm for these tests. To the extent possible, all other test conditions were intended to remain constant for all fuels.

#### ***Package Boiler Simulator***

The package boiler simulator (PBS) is a 3x10<sup>6</sup> Btu/hr horizontally-fired unit capable of burning natural gas or liquid fuels in an environment that simulates a water wall boiler. A schematic of the unit is shown in Figure 4-1. The PBS burner has an air-atomizing nozzle that is capable of handling the unit's full load heat input, based on No. 6 fuel oil. Since the PBS was operated at heat input rates well below full load, it was adequate to handle the higher volume of Orimulsion required to maintain a steady heat input rate. The PBS has a 10 in. inside diameter refractory lined burner section connected to a water cooled transition section of the same inside diameter. The transition section allows staged air or fuel injection through radial or axial ports or through two ports on the horizontal axis aligned 45° from the unit centerline. The transition section connects to the Dowtherm cooled boiler section, which has a 24 in. inside diameter and is 110 in. long. The combustion gases pass out of the boiler section to the vertical stack, where sampling ports are located for taking extractive samples. Inspection and access ports for injection probes or optical sampling are located along the boiler wall and at the stack end of the boiler.

Flue gases from the PBS are ducted to the facility's air pollution control system (APCS), which consists of a 4x10<sup>6</sup> Btu/hr secondary combustion chamber, a fabric filter, and a wet acid gas scrubber. The APCS allows the PBS to operate under poor combustion conditions that intentionally generate higher than normal pollutant emissions during research studies without emitting those excessive pollutants to the environment. The PBS has been used in studies of low NO<sub>x</sub> combustion and reburning for control of NO<sub>x</sub> (Linak et al. 1985, Miller et al. 1998).

**Table 4-1.** Test matrix for EPA pilot-scale tests of Orimulsion air pollutant emissions.

Condition	1	2	3
Fuel	Orimulsion 100	Orimulsion 400	No. 6 Fuel Oil
Boiler Load (Btu/hr)	1,000,000	1,000,000	1,000,000
Excess O <sub>2</sub> (%) <sup>(1)</sup>	3	3	3
MgOH Injection	No	Yes	No
Number of test runs	4	4	4
CO, CO <sub>2</sub> , NO <sub>x</sub> , O <sub>2</sub> , SO <sub>2</sub> , THC (CEMs)	Continuous during test	Continuous during test	Continuous during test
PM concentration (Method 5)	3 tests	3 tests	3 tests
Particle Size Distribution (cascade impactor)	3 tests	3 tests	3 tests
Particle Size Distribution (SMPS)	1 test (5 or more runs per test)	1 test (5 or more runs per test)	1 test (5 or more runs per test)
Metal concentration (Method 29)	3 tests	3 tests	3 tests
Volatile Organic concentration (Method 0010)	3 tests	3 tests	3 tests
Semivolatile organic concentration (Method 0030)	3 tests	3 tests	3 tests
SO <sub>3</sub> <sup>(2)</sup> (MACS train)	3 tests	3 tests	3 tests

1. Actual test O<sub>2</sub> level was intended to be set based on the minimum O<sub>2</sub> at which CO remained less than 50-100 ppm.

2. Miniature acid-condensation system (DeVito and Smith 1991)

## Fuel Supply System

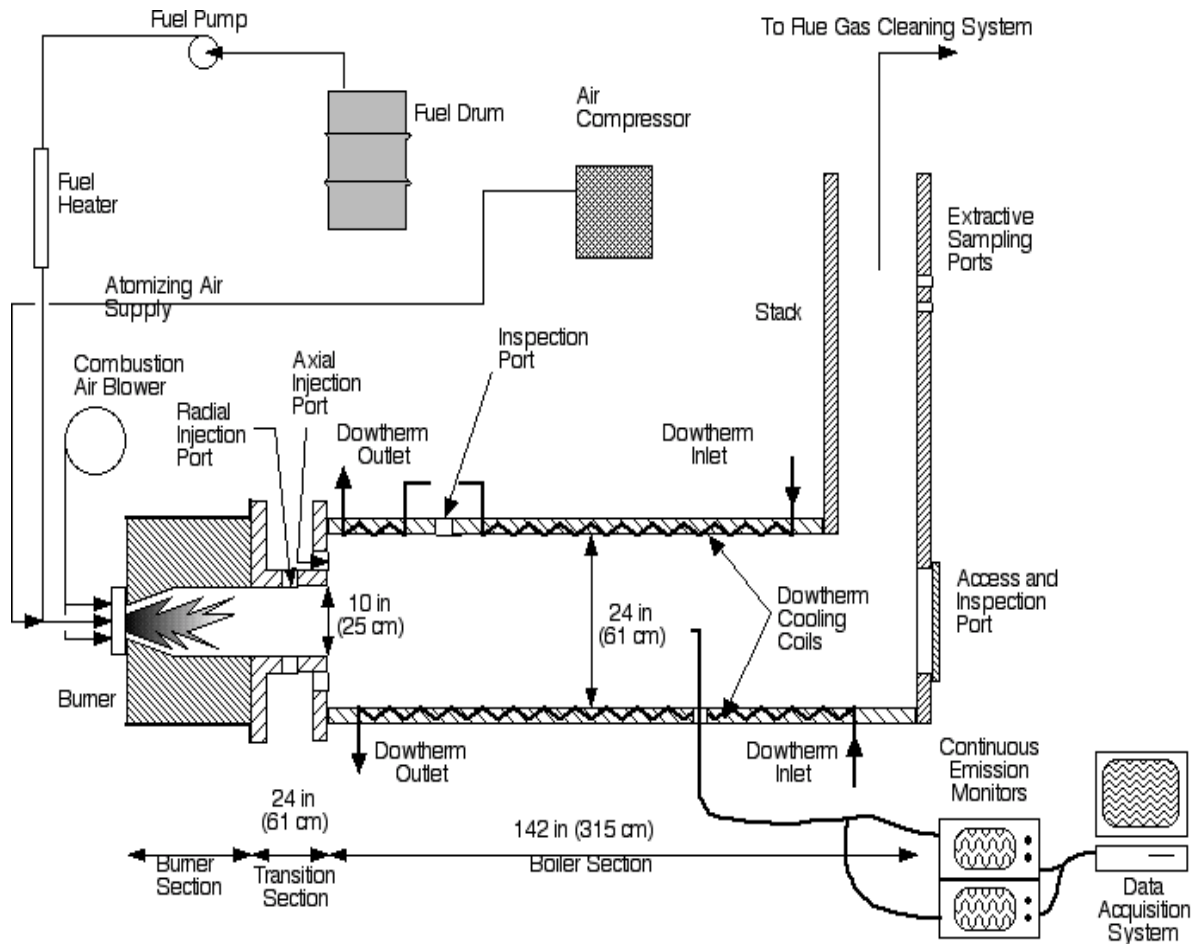
The fuel supply system can influence the stability of emulsified fuels such as Orimulsion. The system should minimize shear rates through pumps, piping, and fittings as much as possible, and should be able to maintain the appropriate temperature range during operation. The original fuel supply system used by the PBS was designed for heavy fuel oil and required modification before Orimulsion could be fed to the boiler. During operation with heavy fuel oil, the original fuel supply system (shown schematically in Figure 4-2) was used.

For operation with Orimulsion 100 and Orimulsion 400, the fuel supply system was modified to use a lower shear Moyno pump rather than the original gear pump and to eliminate the pressure relief valves and the continuous circulation loop used in the original supply system. The modified fuel supply system is shown in Figure 4-3.

A Mg-based additive was injected into the boiler during testing of Orimulsion 400. The additive was Mg(OH)<sub>2</sub>, and was injected into the flame at a rate of between 0.35 and 0.54 g/min during operation at 1x10<sup>6</sup> Btu/hr. This injection rate resulted in a molar ratio of between 2.1 and 3.8 mol Mg to 1 mol V in the fuel.

## Instrumentation

The PBS has continuous emission monitors (CEMs) for measurement of combustion gas composition. Concentrations of CO, CO<sub>2</sub>, NO<sub>x</sub>, O<sub>2</sub>, SO<sub>2</sub>, and THC are measured by CEMs and



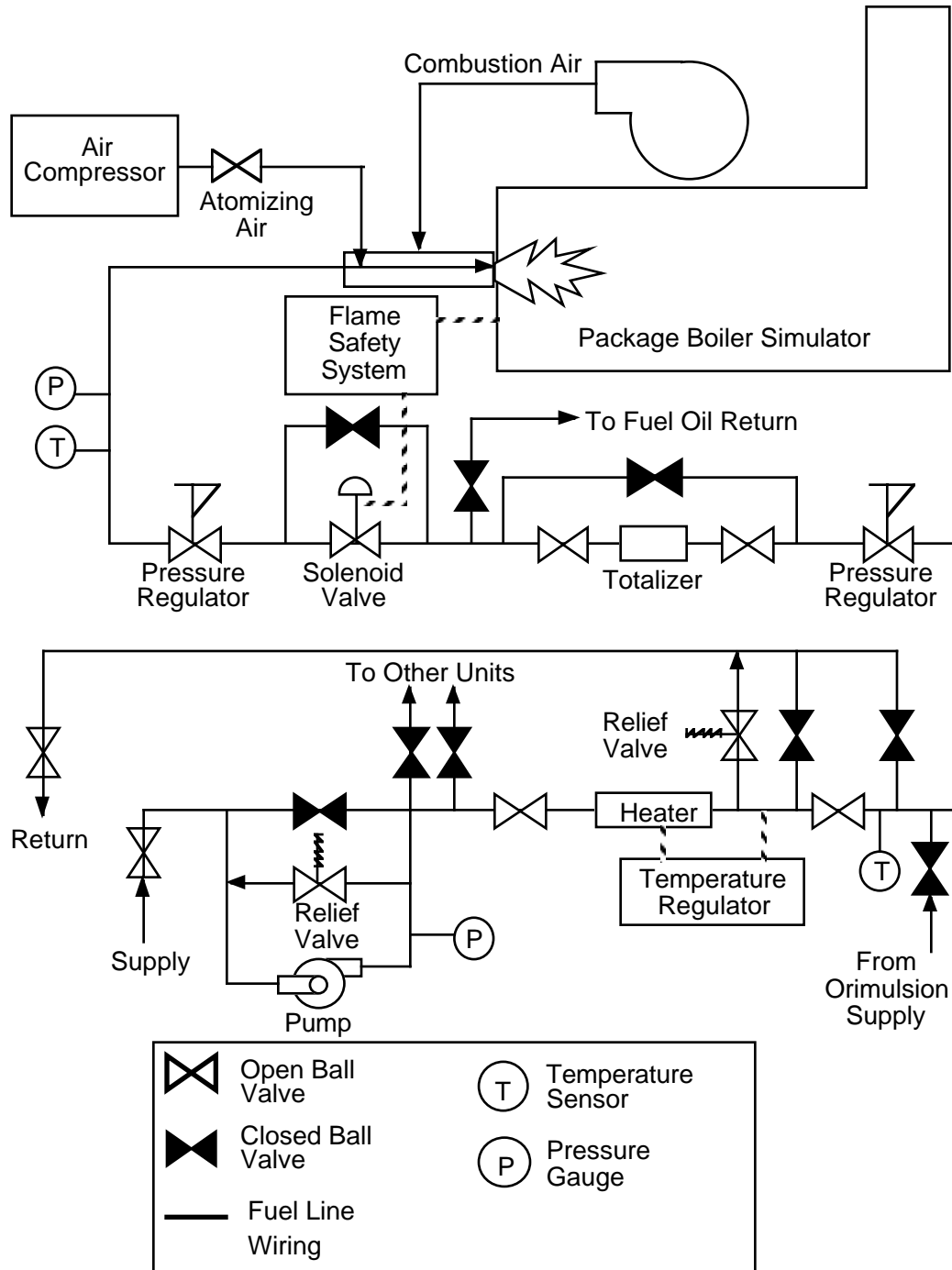
**Figure 4-1.** Schematic of Package Boiler Simulator.

continuously recorded using a computerized data acquisition system (DAS). Stack gases are extracted through a fixed stainless steel probe into Teflon® tubing and transported to the CEM sample conditioning system. The sample gases are dried using a Haneson® dryer and particles are removed by a filter. A portion of the sample is then diverted to the NO<sub>x</sub> analyzer, with the remaining sample passing through a Dryrite® canister and then to the other gas analyzers. THC measurements use a heated stainless steel sampling line that is maintained at 350 °F. The CEM system is shown schematically in Figure 4-4.

#### **Continuous Emission Monitors**

The CO and CO<sub>2</sub> analyzers were Rosemount® model 880A infrared analyzers. Two CO analyzers were used, one having an operating range of 0 to 1000 ppm (CO low) and one having an operating range of 0 to 5% (CO high). The CO<sub>2</sub> analyzer has an operating range of 0 to 20%. A Rosemount® model 951A chemiluminescence NO<sub>x</sub> analyzer was used to measure concentrations of NO and NO<sub>2</sub> in the range of 0 to 1000 ppm. The analyzer can be used to measure either NO or NO<sub>x</sub>. In the NO<sub>x</sub> operating mode, the unit converts any NO<sub>2</sub> to NO prior to porting the gas to the detector. The analyzer was operated in NO mode during the test program.

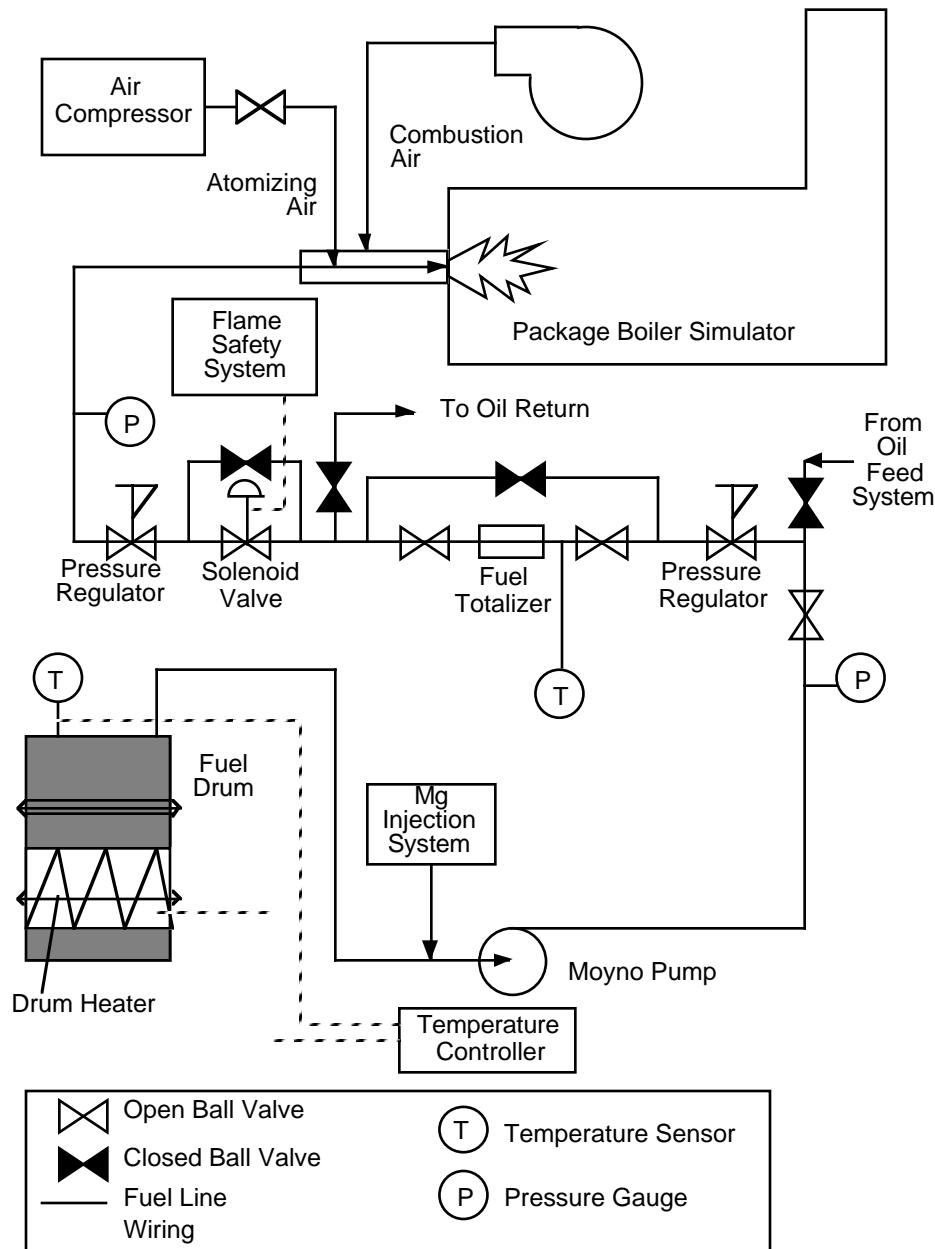
The O<sub>2</sub> analyzer was a Rosemount® model 755R paramagnetic analyzer, with a measurement range of 0 to 25%. SO<sub>2</sub> concentrations were measured using a Du Pont photometric model 400 analyzer. THC was measured using a Rosemount® 402 hydrocarbon analyzer, which operates using a flame



ionization detector. The THC measurement is given as equivalent methane ( $\text{CH}_4$ ), and has an operating range of 0 to 50,000 ppm.

### Data Acquisition System

The DAS is a computer-based system separate from the CEMs. It uses a Macintosh® computer and Strawberry Tree® data acquisition cards, and logs inputs from each of the CEMs at constant intervals

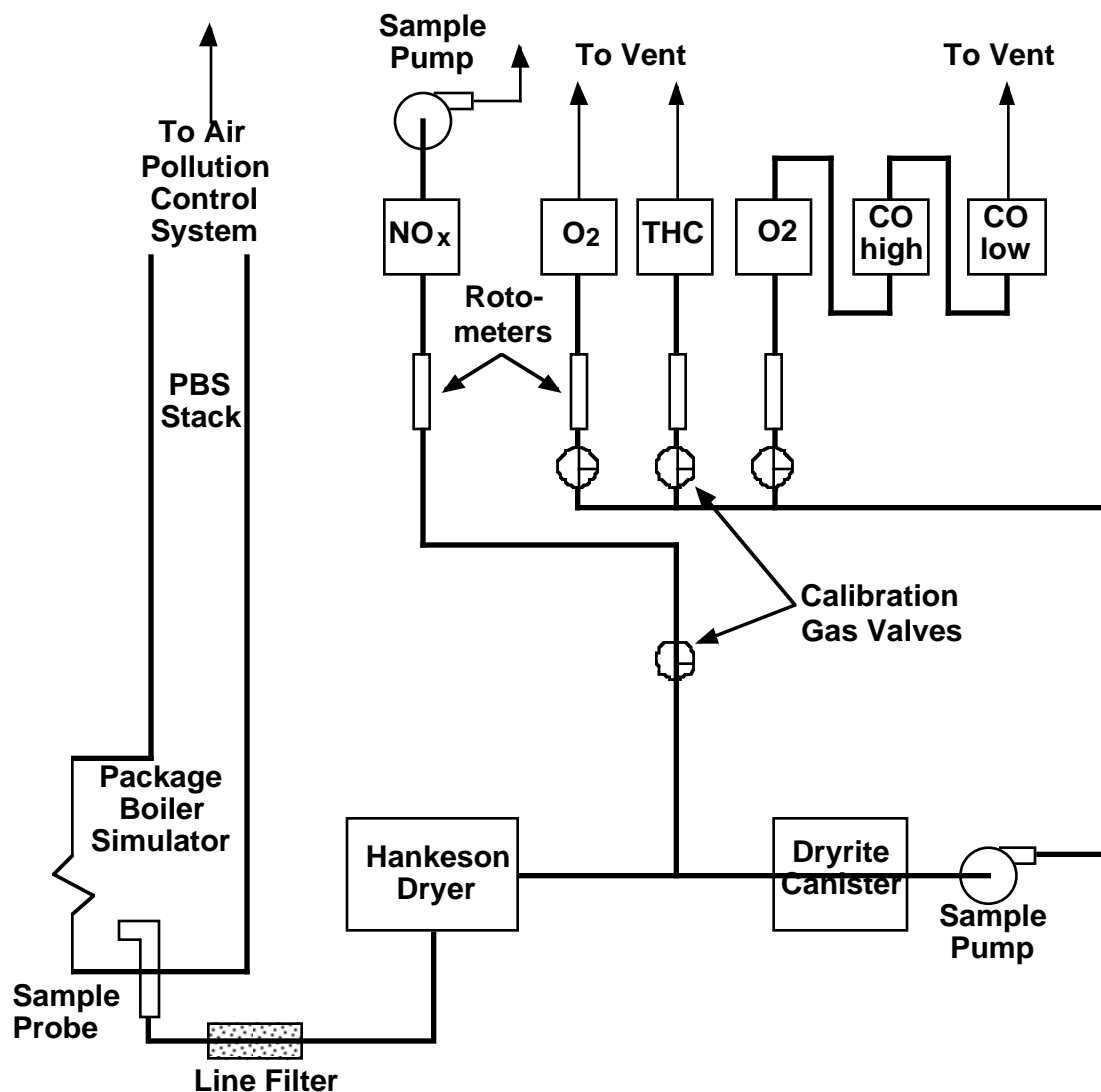


**Figure 4-3.** Schematic of fuel feed system for Orimulsion 100 and Orimulsion 400.

that can be adjusted according to the needs of each experiment. Selected data are shown on the screen during operation, and all data are stored on the unit's hard disk drive for later retrieval and reduction. Data logging is conducted only during testing or calibration.

### Dilution Sampling System

A dilution sampling system (shown schematically in Figure 4-5) was used to collect samples for use in toxicity testing by EPA's National Health and Environmental Effects Research Laboratory (NHEERL). This system collects large quantities of PM for the toxicological studies. The system is capable of sampling 10 ft<sup>3</sup>/min of flue gas. The sample passes through a modified Source Assessment Sampling System (SASS) cyclone and is then diluted with 100 ft<sup>3</sup>/min of clean ambient



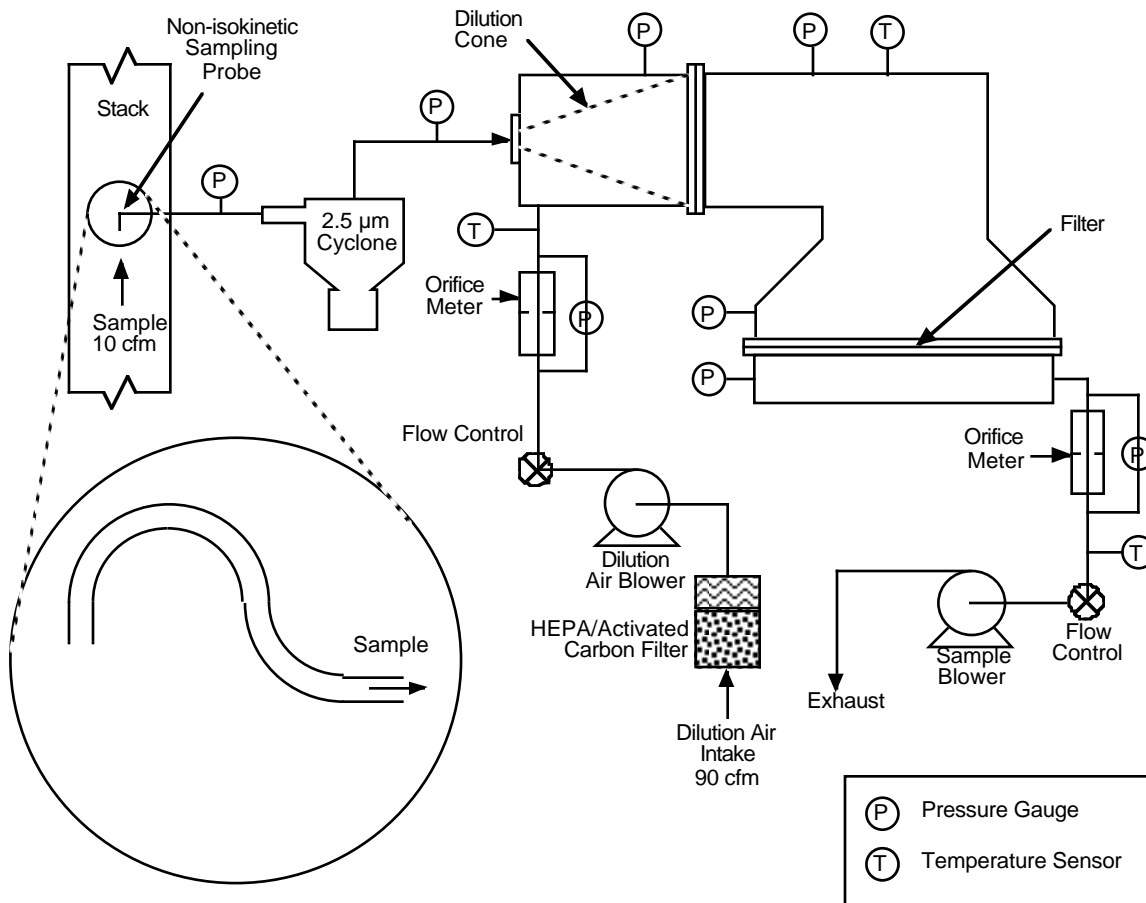
**Figure 4-4.** Schematic of continuous emission monitoring system.

air using a perforated cone assembly. Rapid uniform dilution cools the sampled gases and PM to nearly ambient temperature within a residence time of approximate 3 s. Isokinetic sampling conditions were not possible for these large dilution samples. Further details regarding the dilution sampler's construction and operation are presented by Steele et al. (1988).

The SASS cyclone preseparator produces 50 and 95% particle collection efficiencies at approximately 1.8 and 2.5  $\mu\text{m}$  aerodynamic diameter, respectively, at standard conditions. The small fraction of PM that passes through the cyclone is collected on large (25.5 in. diameter) Teflon coated glass fiber filters for subsequent analysis (Linak et al. 1999).

#### **Scanning Mobility Particle Sizer**

A Thermo Systems, Inc., scanning mobility particle sizer (SMPS) was used to measure particle size



**Figure 4-5.** Schematic of high volume dilution sampling system.

distributions for particles with diameters in the range of 0.01 to 1.0  $\mu\text{m}$  diameter. The SMPS classifies and counts particles using principles of charged particle mobility through an electric field. The SMPS was configured to yield 54 channels evenly spaced (logarithmically) over the operating size range. SMPS samples were extracted from the PBS stack isokinetically and diluted with filtered nitrogen ( $\text{N}_2$ ) to a ratio of approximately 5 parts  $\text{N}_2$  to 1 part stack gas. Dilution flow was controlled using a mass flow controller and total sample flow measured with a laminar flow element. Both devices were calibrated using a Gilibrator® bubble flow meter. Additional details of the system design and operation are described by Scotto et al. (1992) and Linak et al. (1994).

### Scanning Electron Microscope

Samples were also collected on silver membrane filters and analyzed using a SEM equipped with an energy dispersive x-ray (EDX) spectrometer. These analyses provided morphological information of individual particles. Particles were extracted from the stack location using the same sampling system and dilution as used by the SMPS described above. However, these particles were directed through a stainless steel filter holder containing a 47 mm silver membrane filter. Sampling times of approximately 30-60 s provided a sufficient quantity of particles for analysis. Silver filters were used to improve conductivity and minimize particle charging caused by the electron beam.

### Sampling Methods

#### *EPA Methods 5 and 29*

Particle concentrations were determined using EPA Method 5 (EPA 1994); EPA Method 29 was used to determine metal concentrations in the flue gases (Garg 1990). The particle concentration option

was used during the Method 29 operation, but the mercury option was not used, meaning that the Method 5 procedure used the same train as Method 29, allowing a single sampling train to be used to determine both PM mass and metal concentrations.

A blank Method 29 sampling train was prepared and set up at the sampling location, and remained at that location for the duration of sampling. The blank train filter was weighed, and the solutions were recovered and analyzed with the remaining Method 29 sampling trains to identify possible contamination. Two Method 29 trains were spiked with known concentrations of target metals and subsequently analyzed with the other samples to determine laboratory recovery of known concentrations. Chapter 11 (Quality Assurance) provides additional details concerning the blanks and spiked samples. The Method 29 samples were analyzed for As, Be, Cd, Cr, Cu, Fe, Mn, Mg, Ni, Sb, V, and Zn.

### ***EPA Methods 0010 and 0030***

EPA Method 0030 was used to sample the concentration of volatile organic compounds (VOCs) in the flue gases of all three fuels (EPA 1986a). EPA Method 0010 (sometimes referred to as a Modified Method 5) was used to sample semivolatile organic compounds for all three test conditions (EPA 1986b). Three samples were taken for the semivolatile organic compounds and triplicate VOC samples were taken.

Both EPA Method 0010 and 0030 sampling trains were prepared, set up at the sampling location, and analyzed to identify possible contamination.

### ***Modified CARB Method 501***

Particle size distributions were also measured using an in-stack cascade impactor. An Anderson® impactor was used in a modified California Air Resources Board (CARB) Method 501 (CARB 1990). This method allows size-segregated samples to be collected for determining either the relative mass fractions in each size range or the concentration of trace elements in each size range. These tests modified the CARB method slightly to allow for use in the research combustor. The CARB method places the impactor precutter in the stack. However, the PBS stack is too small to allow in situ placement of the impactor, so a buttonhook nozzle is used rather than the straight nozzle specified in the CARB method. Fewer runs are conducted during research testing than are called for in the CARB method, with only three runs used during research testing rather than the seven runs specified by the CARB method.

A blank CARB 501 impactor was also prepared and set up at the sampling location, and its filters subsequently weighed, to evaluate any contamination of the filters during the sampling procedures.